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AN INVESTIGATION OF METHODS FOR 100-MILLIBAR CONTOUR AND WIND PROGNOSIS

HARRY N. FARNSWORTH
and
JOSEPH D. MACKENZIE

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AN INVESTIGATION OF METHODS
FOR
100-MILLIBAR CONTOUR AND WIND PROGNOSIS

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and

Joseph D. Mackenzie

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by

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Lieutenant, United States Navy

and

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Lieutenant, United States Navy

Submitted in partial fulfillment of
the requirements for the degree of

MASTER OF SCIENCE
IN
METEOROLOGY

United States Naval Postgraduate School
Monterey, California

1960

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ABSTRACT

The continual increase in operating altitudes of jet-powered aircraft has resulted in meteorological requirements for successively higher levels. Present operational procedures necessitate prognoses up to 200 mb but the increasing number of high performance aircraft will shortly require prognostication to at least the 100-mb level.

Several techniques for 24-hour 100-mb prognosis are investigated including: (a) direct prognosis from 100-mb data, (b) direct movement of 100-mb height change centers, (c) use of prognostic 500-mb space-mean height and relative vorticity, (d) extrapolation of a 100-mb prognosis from 500 mb using graphical addition of various 500/100-mb thickness patterns to the 500-mb prognostic chart, (e) graphical addition of 500-mb space-mean and space-time mean charts and a mean 500/100-mb thickness pattern, and (f) persistence.

The latter three, being the most promising, are statistically evaluated as 100-mb prognostic techniques. Verification is accomplished through pattern resemblance, spot forecasts and a grid system for determining contour gradients. Persistence proved to be superior.

This study represents a joint effort by the authors. The authors are deeply indebted to Assistant Professor Robert J. Renard of the Department of Meteorology and Oceanography, United States Naval Postgraduate School, for his invaluable aid throughout the investigation. Further assistance of the following is hereby acknowledged: CDR John A. Mirabito, USN, U.S. Navy Fleet Weather Central, Washington, D.C., and the U.S.

Weather Bureau's National Meteorological Center in obtaining the analyzed 100-mb charts used in this study, and Mr. R. Corday Counts, Jr., and personnel of the San Francisco office of the U.S. Weather Bureau for their suggestions and informative discussions. The authors also wish to thank their wives for their patience and aid in preparation and preliminary typing of this manuscript.

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I. Introduction

The coming of the jet engine as an aircraft power source has steadily pushed operational flight levels upward. Demands on flight forecasting have increased commensurably; however, fulfillment of these demands has lagged considerably. During the recent reign of the piston-engined transport, the 500-mb surface became the primary forecast level for most long-range aircraft operations. This triggered considerable research into 500-mb forecasting techniques and the development of increasingly accurate prognoses. Numerical prognosis, being especially suited to the free atmosphere near the statistical level of non-divergence, became operational for 500-mb prognosis with results currently equalling or bettering the best conventional approach.

At present the United States Weather Bureau's National Meteorological Center makes daily prognoses of the 300-mb surface and the 500-mb surface for facsimile transmission. The 200-mb surface, analyzed twice daily, and the 100-mb, analyzed once daily, are both transmitted via facsimile, but neither are prognosticated for transmission purposes. Weather Bureau offices responsible for high altitude flight forecasting generally analyze and prognosticate levels up to the 200-mb surface for their areas of responsibility, but as yet no prognosis of the 100-mb surface is made.

The atmosphere near 100-mb (United States Standard Atmosphere height: 53,170 feet) is currently used by a relatively small number of high performance military aircraft; however, their number is increasing and an invasion of this

air space by commercial aircraft is not too far in the future. It is possible that numerical prognosis for this level will become feasible before a large scale requirement exists, but until much more accurate information becomes available through improved atmospheric soundings, the extension of numerical prognosis to the 100-mb level is doubtful. In the interim, a need is developing, especially in the military, for a validated means of 100-mb prognosis. This study is a search for such a method.

Having faith in the ultimate development of numerical prognostication of the 100-mb surface, the authors limited their investigation to procedures which: 1) could be employed NOW with presently available data, 2) would be as objective as possible, 3) would be sufficiently accurate to warrant the time spent on the prognosis, 4) would permit considerable assistance by non-professional personnel and 5) would be useful at smaller installations expected to have a low priority in acquiring a computer. The third criterion, although apparently obvious, is especially important since the flow patterns at 100 mb, even by cursory inspection, appear extremely persistent; thus, any technique developed must better persistence both in accuracy and in expenditure of forecast time.

II. Current Status of Data, Analysis, and Prognosis at 100-mb

The 100-mb contour pattern is characterized by a general equatorward increase in contour height. The height difference, pole to equator, is approximately 5000 feet in winter and near 1000 feet in summer [6]. For the most part flow is westerly in both seasons with greatest velocities in winter. Winter is the season of greatest change (least persistence). The most decisive test of any prognostic procedure, using persistence as an investigative criterion, would then be in winter. January was selected as "the winter month" for all prognostic attempts. Analyzed 100-mb charts for January 1959 and 1960 were obtained from the United States Weather Bureau's National Meteorological Center and used in conjuction with that agency's 500-mb analysis as transmitted via facsimile.

The National Meteorological Center analyzes only the 1200Z chart for 100 mb but this was not considered as a critical factor. Muench [6] cautions against use of "off-time" heights and temperatures in 100-mb analysis due to an important diurnal variation. Hence, use of charts 24 hours apart minimizes or eliminates this diurnal effect. Further, a 24-hour prognostic technique was sought and this also lessened any requirement for the 0000Z analysis.

The January 100-mb contour pattern in the vicinity of the North American Continent usually consists of a broad trough over the center of the continent, with a closed low over the Canadian Archipelago region (figs. 1 and 2).

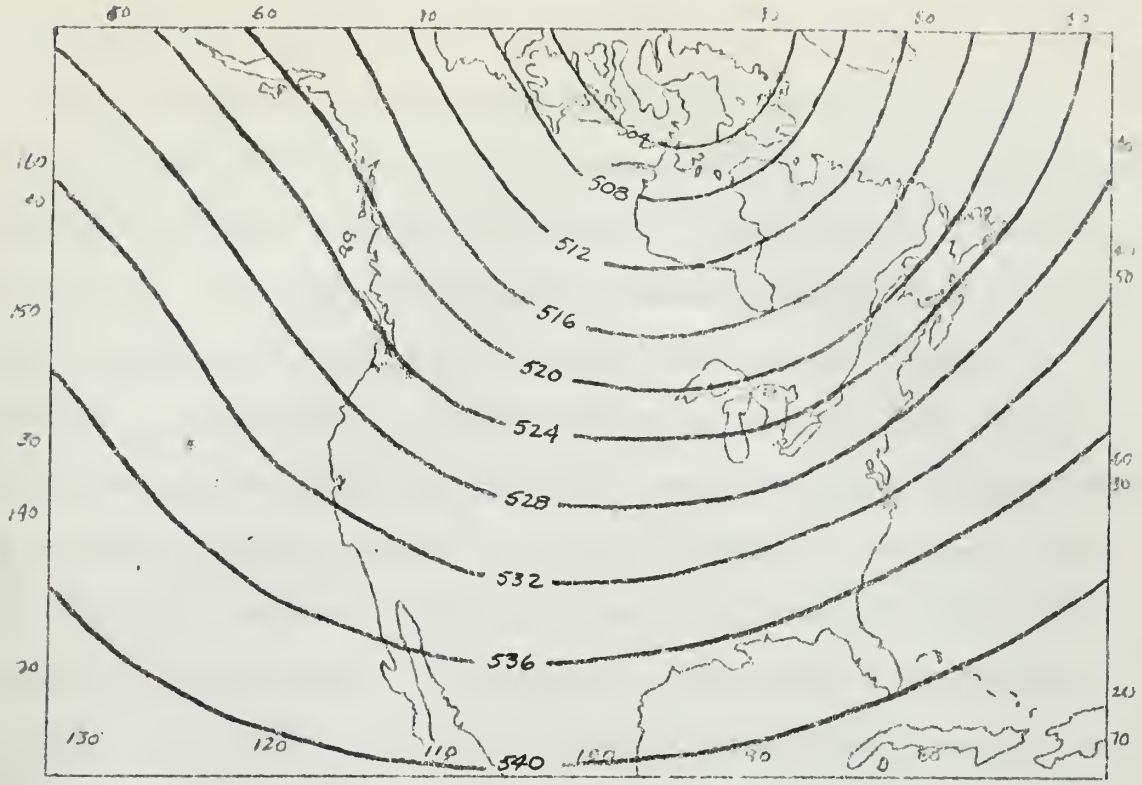


Figure 1. Mean January 100-mb Contours

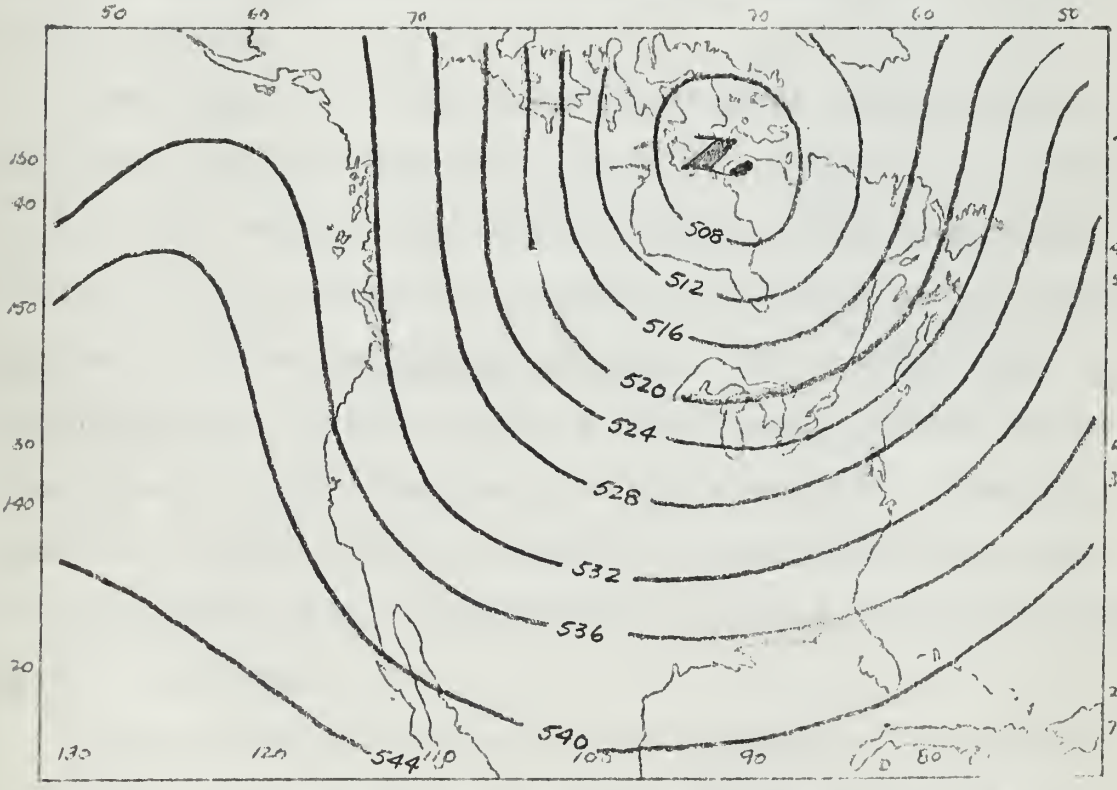


Figure 2. 100-mb Analysis 1200Z 19 January 1959

Occasionally a flat ridge is positioned through the center of the continent with troughs near the coasts (fig. 3). Another variation is a displacement of the central-continent trough northward, attended by zonal flow in middle-latitudes (fig. 4). The 100-mb isohyptic field is essentially of long wave character; however, the existence of short waves is easily substantiated. Thus, the variation in the 100-mb pattern can be explained by short wave movement through the long wave system similar to that at 500-mb. However, the 100-mb short waves, apparently being of lesser amplitude than at 500 mb, tend to modify the long wave circulation rather than establish circulations or wave patterns of their own. In most cases the short waves are noticeable in only a few contours.

The degree to which these minor waves appear on each analyzed chart is dependent on their location (i.e., proximity to one or more reporting stations), their amplitude, history (i.e., existence, position, and amplitude on previous charts), and the individual analyst. The peculiarities of the individual analyst figure significantly in each 100-mb chart due to the subjectivity of the analysis. Using the same data and analytical criteria two analysts may easily produce charts with a significant variation in contour alignment and gradient.

The problem of accuracy of measurement is a major factor in 100-mb analysis and hence affects prognostic verification. Muench [6] has determined that 100-mb radiosonde heights have a standard error of ± 128 feet. This suggests

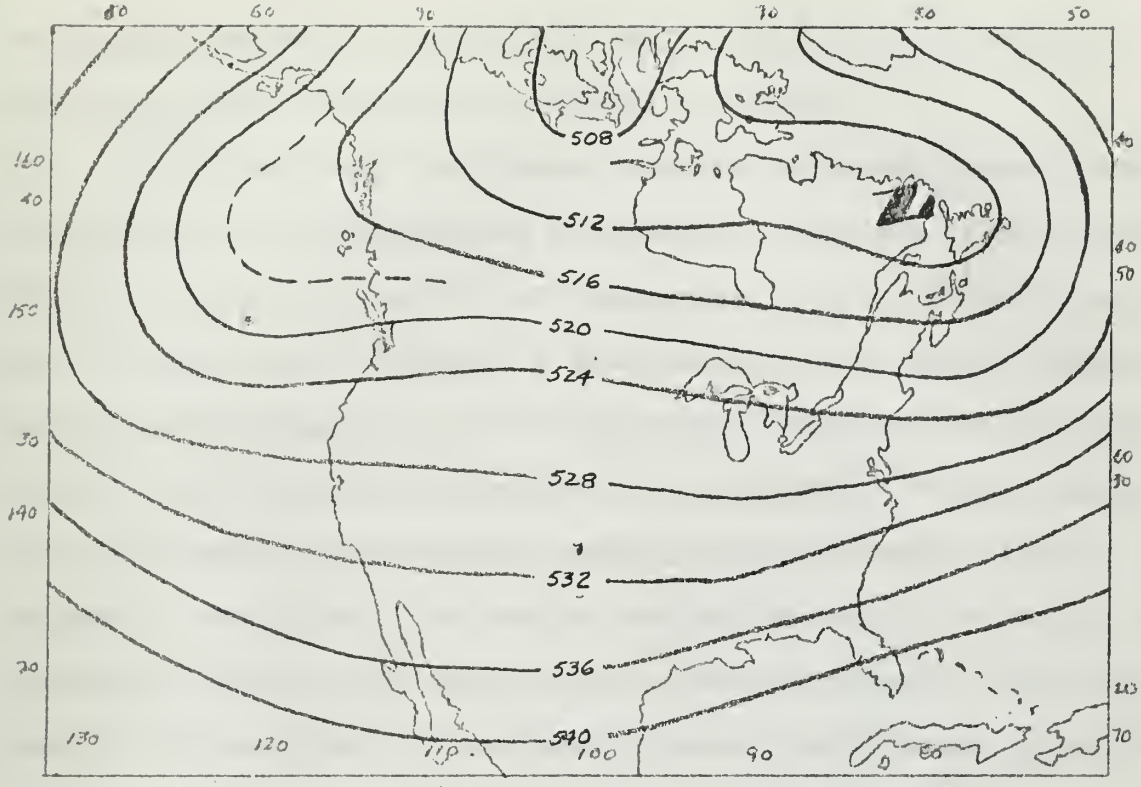


Figure 3. 100-mb Analysis 1200 Z 8 January 1959

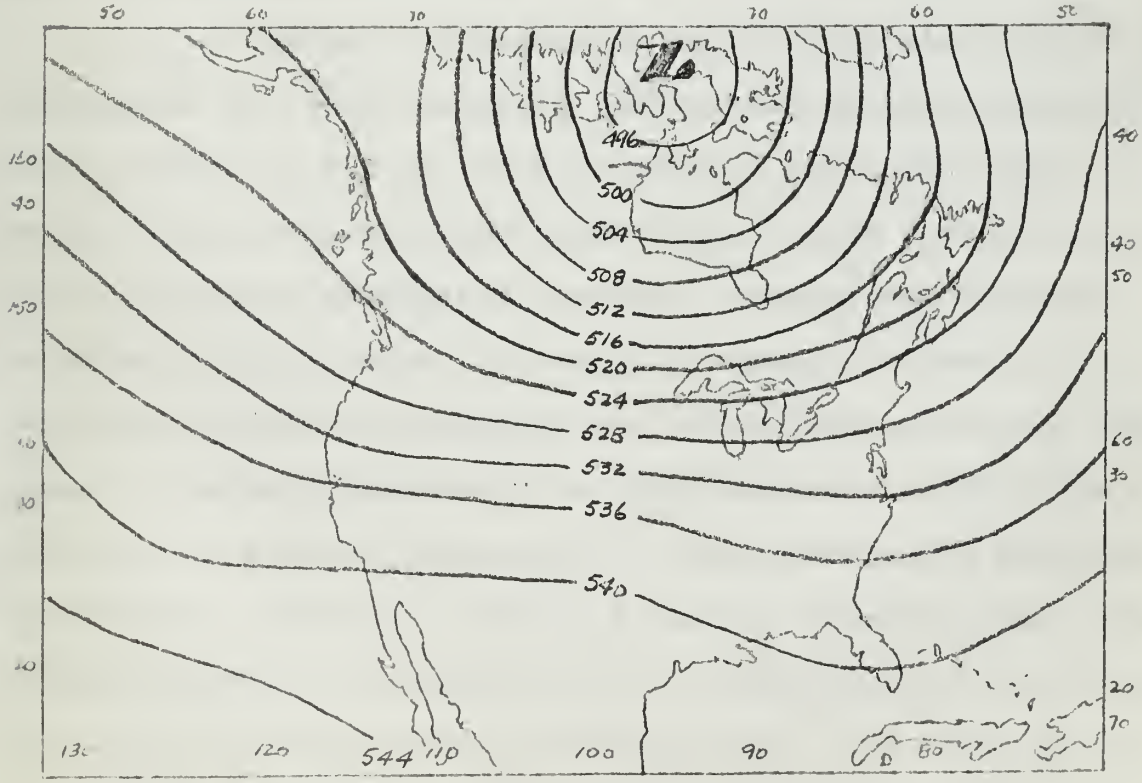


Figure 4. 100-mb Analysis 1200 Z 25 January 1959

a sizable degree of subjectivity in the analysis, and coupled with too few stations reporting 100-mb data, requires a considerable amount of analytical skill to produce an analysis that will have continuity in time and space.

These problems involving analysis accuracy have great significance in determining methods of prognosis. The indistinct features of the 100-mb isohypses (i.e., broad troughs and ridges, etc.), suggest a prognosis of the overall pattern rather than prognosis of the individual features of the pattern. Due to the aforementioned subjectivity of each analysis (and hence of prognostic verification) it soon became apparent that if any objective evaluation was to be made, the analyzed charts would have to be assumed correct. Thus forecasts were verified by analyzed contour heights and geostrophic winds only.

In an analysis of errors in upper level wind forecasts, Ellsaesser [2, 3] established persistency as the best forecast method for 100 mb for time periods up to 36 hours, at which time persistence and climatology become equally as good. At no time does Ellsaesser consider conventional forecast methods of equal value for 100-mb prognosis. However, conventional forecast techniques are effective for 24-hour prognoses of upper tropospheric or stratospheric levels below 100 mb. In general, prognoses at these levels are dependent upon those at 500 mb. This is a logical procedure since the 500-mb surface is recognized as a surface of considerable data, thus is well analyzed and prognosticated. The adaption of numerical techniques to 500-mb prognostication further

strengthens this practice. As examples of techniques for prognosis at upper levels using the 500-mb surface, the work of Hering and Mount [5] and Vederman and Dubofsky [10] is outlined below.

Vertical extrapolation of an upper level contour prognosis from a 500-mb (or any other) base requires some means of adequately determining the layer thickness. If the hypsometric equation is used, an accurate estimate of the temperature at the top and bottom of the layer and of the thermal structure of the layer must be made. Hering and Mount [5] were concerned with prognosticating 200-and 100-mb contour heights. Temperature, contour height and relative vorticity data from 700, 500 and 400 mb were used to extrapolate the 200-and 100-mb patterns. Seasonal regression equations for 200 mb were developed using only 700-and 500-mb contour heights, with a relative vorticity correction added for winter use. A slightly less accurate set of regression equations depended on 500-mb temperature and contour heights. In either case the standard error averaged less than 200 feet.

Regression equations for extrapolation to 100 mb were also determined, however, the results (standard error of estimate approximately 250 feet) were not considered of sufficient accuracy for operational use. They show that a 500-mb to 100-mb thickness determination with a desired accuracy of ±150 feet necessitates knowledge of the mean temperature of the layer to 1°C. This fact virtually eliminates the use of an arithmetic mean temperature in determining the layer thickness since the standard error in radiosonde measurements of

temperature in the upper troposhere and lower stratosphere is near ± 1° C [1] and the thermal structure of the 500/100-mb layer varies considerably with tropopause height.

Vederman and Dubofsky [10] utilized the good correlation between 500-mb and 300-mb heights and the fair correlation between 500-mb and 200-mb heights in developing a technique for 300 and 200 mb. For the winter months they determined that a nearly linear relationship exists between 500-and 300-mb contour heights. The 300-mb prognosis consists of merely relabeling the prognostic 500-mb contours with application of several rules for slight modification of the resulting pattern. The technique for the 200-mb prognosis follows similar lines; however, it is complicated slightly by addition of a relative vorticity parameter. Experience with this technique for 300-mb prognosis at the United States Naval Postgraduate School indicates accuracy equalling that of the 500-mb chart from which the prognosis was derived.

The most complete study of the 100-mb surface, to date, is that of Panofsky, Krawitz and Julian [9] , under a United States Navy sponsored project. Although not specifically a study for prognostic purposes the results are applicable to prognosis and one such technique was outlined. The concept of the 100-mb surface as a matching level for the 500-mb surface was advanced and utilized in specification of 100-mb wind velocities. The matching level for the 500-mb surface varies with time and latitude being near 80 mb over the southern United States and approximately 125 mb over Canada, with 100 mb a good average in the 30-45° latitude belt.

The close relationship between the 500-mb and 100-mb surfaces was shown by a correlation study involving the change in wind between 500 mb and 100 mb ($\Delta V_{500-100}$), wind at 500 mb (V_{500}) and height of the 500-mb surface. Graphs empirically relating $\Delta V_{500-100}$ to V_{500} resulted, but standard errors in determining the former made this untenable for prognostic application. Results were improved slightly when smoothed profiles were used.

Based on the principle of the persistence of long waves in the vertical, a specification of the 100-mb flow was made using space smoothed 500-mb contour patterns. Specifically a 500-mb 20° diamond grid space-mean pattern was proposed as a 12-hour 100-mb prognosis with contour spacing determined as follows: for 500-mb space-mean height $\geq$ 17,400 feet spacing per 5° latitude equal to that of the space mean; $\leq$ 17,200 feet spacing per 5° latitude equal to twice that of the space mean.

The 20° diamond grid was chosen as being superior to other grid distances and any combination of time and space smoothing. It was used for a ten-day forecast period in January 1956 with a standard error in geostrophic wind direction equal to 17° for the first five days and 28° for the second five-day period. The standard error of specifying the contour gradient was 119 feet and 133 feet for the respective five-day periods.

III. Prognostic Investigations

The objective of this investigation, namely, to seek a 100-mb prognostic technique that would be objective, simple and rapid, limited the study to two basic approaches: 1) direct prognosis from 100-mb data, not necessarily analyzed, and/or 2) prognosis by extrapolation from data at a lower level (not necessarily analyzed or prognosticated). The 500-mb level was used as the sole "lower level" in all vertical extrapolation techniques.

The procedures used in search of a satisfactory prognostic technique are discussed in the following paragraphs.

A. Direct prognosis of the movement of 100-mb systems using conventional prognostic techniques.

Based on the concept of Panofsky [9] that the matching level for 500 mb is near 100 mb, attempts were made to adapt certain 500-mb techniques for use at 100 mb. The 500-mb techniques considered were Bjerknes' eccentricity formula*, constant absolute vorticity trajectories [8] and the grid method [13]. Attempts to use these techniques unmodified gave very poor results and in many cases forecast a direction opposite to the actual direction of movement.

Further study was made into the possibility of either modifying the above techniques or developing new techniques for use at 100 mb. This approach proved unsuccessful for the prediction of center movements because of the existence of

*Departmental Notes, Department of Meteorology and Oceanography, United States Naval Postgraduate School, Monterey, California.

relatively few closed centers at this level and their inconsistent movement. The development of a method for predicting trough movement faired badly on another account, namely, the inablility to uniquely locate the usually broad troughs.

B. Vertical Extrapolation of a 100-mb prognosis utilizing the 500-mb prognosis.

In Vederman and Dubofsky's [10] method for the prognosis of the 300-mb and 200-mb levels, the 500-mb prognosis is used as a base from which the 300-mb and 200-mb prognoses are obtained. This method yields immediately a complete pattern rather than the forecast positions of features about which the prognostic chart can be constructed. The problem of the 100-mb prognosis was approached in the same manner here.

Since the 500-mb level is a level of sufficient, accurate data, and since in the mean, the 100-mb and 500-mb patterns show marked similarity [7,12] , the 500-mb level was also chosen as the base level for the prognosis at 100 mb. Also, conventional and numerical techniques for the 500-mb prognosis have reached a state of refinement so that the use of a 500-mb prognostic chart as a basis for the prognosis of another level will introduce a minimum of error.

1. Graphical addition of the current 500/100-mb thickness pattern to the 24-hour 500-mb prognosis.

a. The first attempt along this line involved the use of the current (0 hours) thickness pattern between 500 and 100 mb and the "perfect 24-hour prog" (i.e. at 0+24 hours)

500-mb chart. The present thickness pattern, held geographically stationary, was graphically added to the prognostic 500-mb chart. After making a number of 100-mb prognoses using this method, none of which were successful as a prognosis, the method was discontinued.

b. The second attempt differed from the first in that the present thickness pattern was not held geographically stationary. Thickness lines were moved with the 500-mb features (i.e. the thickness over a particular 500-mb low or high center was maintained for a 24 hour period). This method also showed very little initial promise and was not developed further.

2. Graphical addition of a monthly mean 500/100-mb thickness pattern and the 500-mb 24-hour prognosis.

During the above investigations it was noted that there is a marked similarity in the shape of the 500/100-mb thickness patterns from day to day. Therefore, the use of a time-mean thickness pattern was considered. A monthly mean was decided upon and the mean thickness pattern (fig. 5) was obtained using the mean January 500- [7] and 100-mb [12] patterns.

The graphical addition of the mean thickness and the 500-mb prognosis is simply a repeat of the first of the previous methods, but uses the mean thickness rather than the present thickness. The first few prognoses made using this method closely resembled the actual 100-mb chart and produced very good grid scores.* However, the prognostic

*This method of verification is discussed in Chapter IV.

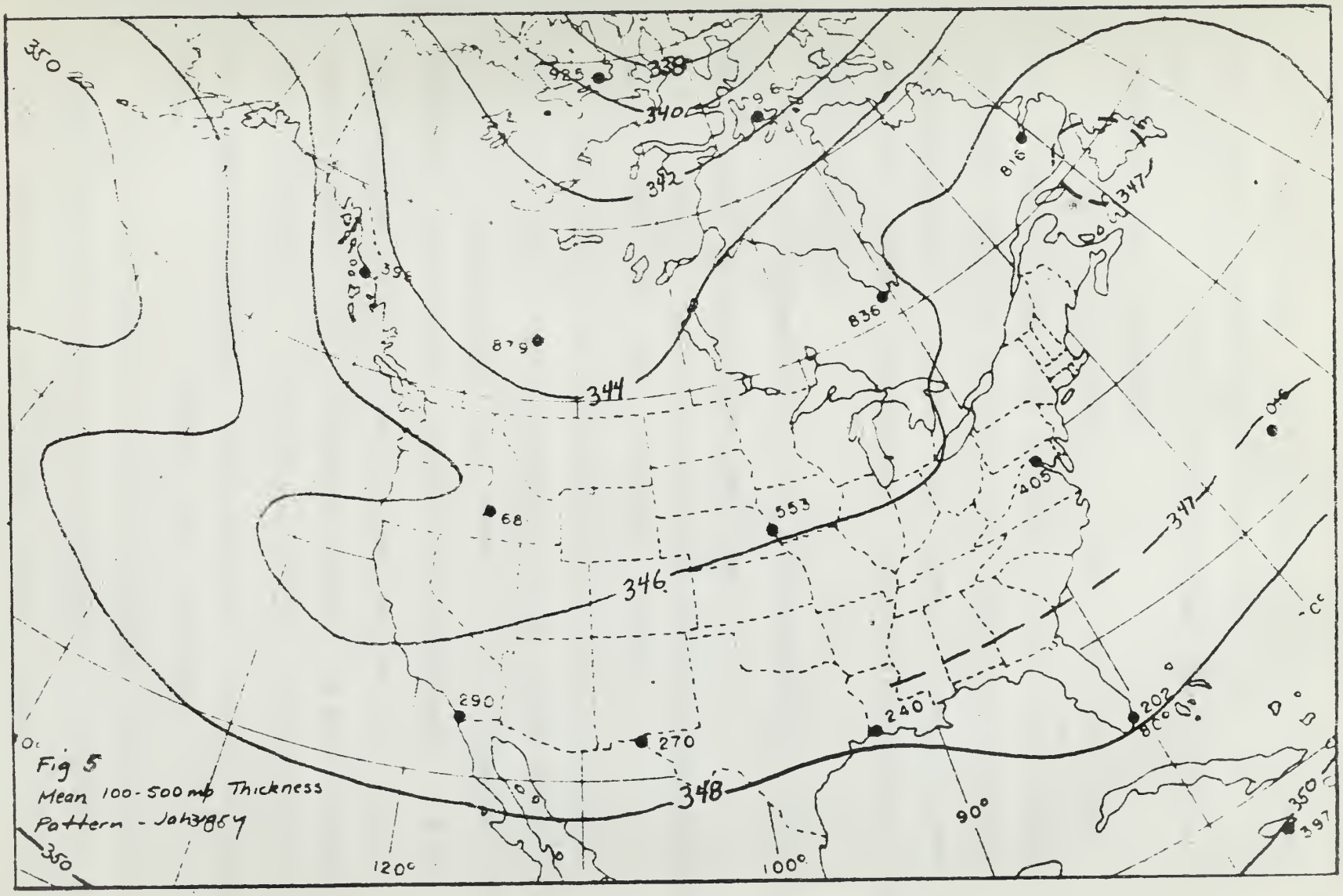


Fig 5
Mean 100-500 mb Thickness
Pattern - Jan 31 1964

heights in the higher latitudes were too high and there was a general vagueness in the prognostic pattern in the vicinity of the northward bulge of the 34,600-foot thickness line over the northeastern United States (fig. 5). Later prognostic charts based on this approach were not as successful as the first few.

A subjective modification to the basic thickness pattern (fig. 6) was made in hopes of achieving results compatable with the results of the first few prognoses. Although there was a slight improvement it was not great enough to warrant continuance of the investigation of this general approach.

C. Vertical Extrapolation of a 100-mb prognosis utilizing 500-mb space or space-time smoothing.

1. Graphical addition of the 500-mb space mean and the current 500/100-mb daily thickness pattern.

Panofsky [9] has recommended the use of the 500-mb space mean as a 12-hour prognosis of the 100-mb flow pattern. A 500-mb space mean plus the current daily thickness pattern was used in an attempt to extend the space mean to a 24-hour prognosis and to obtain 100-mb contour smoothing. Several tests of this technique resulted in grid scores comparable to those of persistence, but the prognoses at no time were significantly better than persistence so further evaluations of this technique were not made.

The space mean used in this technique was obtained in a manner similar to that of Fjortoft [4] . It differed only in that the charts are off-set a grid distance of 12° latitude

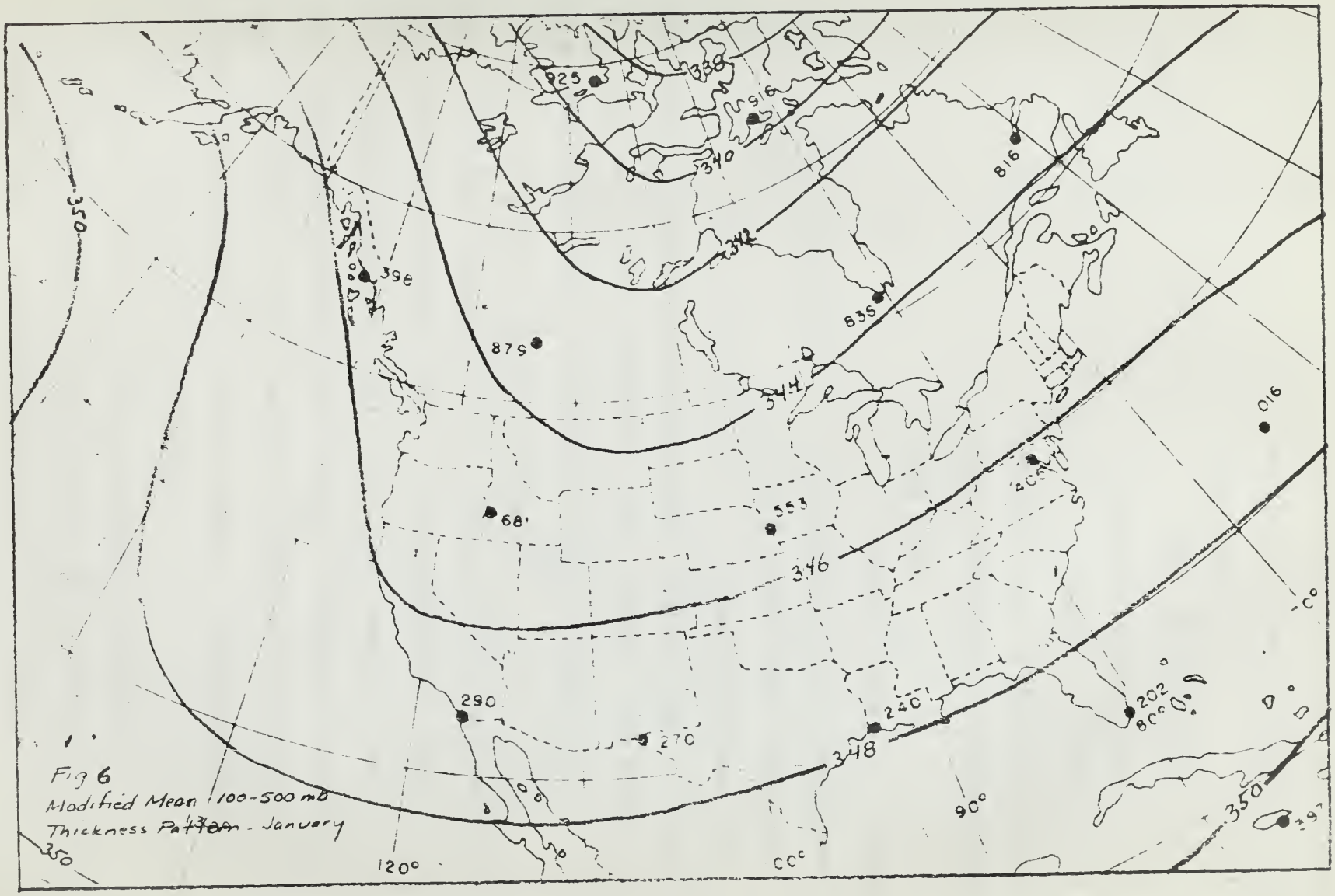


Fig 6
Modified Mean 100-500 mb
Thickness Pattern - January

measured at 30° North. This method computes the space mean height at a particular point as being equal to

$$\frac{1}{4}\left(Z_N + Z_S + Z_E + Z_W\right)$$

as illustrated in figure 7.

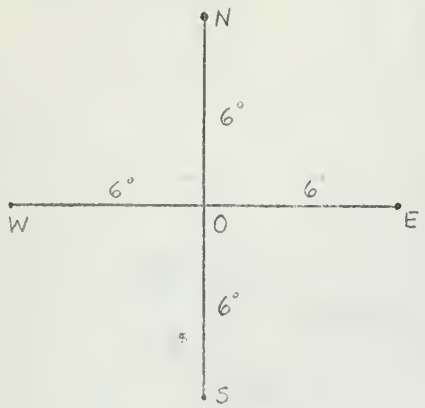


Fig. 7 12° Square grid for determining space-mean heights

2. Graphical addition of a modified mean 500/100-mb thickness pattern and a 500-mb space-time mean.

Another attempt to develop a technique for the prognosis of the 100-mb level employed space smoothing of a different form. A space-time mean was constructed using the current analyzed 500-mb chart (0 hours) and the 24-hour 500-mb prognosis (0+24 hours). The 500-mb space-time mean height at the grid center is equal to

$$\frac{1}{4}\left[\left(Z_N + Z_E\right)_0 + \left(Z_S + Z_W\right)_{0+24}\right]$$

After obtaining a space-time mean (fig. 8), the mean thickness pattern as modified (fig. 6) was graphically added to give a 100-mb prognosis. Again the first charts obtained by using this method showed good results. However, subsequent prognoses failed to yield results sufficiently accurate to establish this method as a valid means of prognostication.

D. Other prognostic investigations

1. Persistence as a 100-mb prognostic technique.

In substantiation of Elsaesser's [2,3] conclusion that persistency is the best method for 100-mb prognosis and

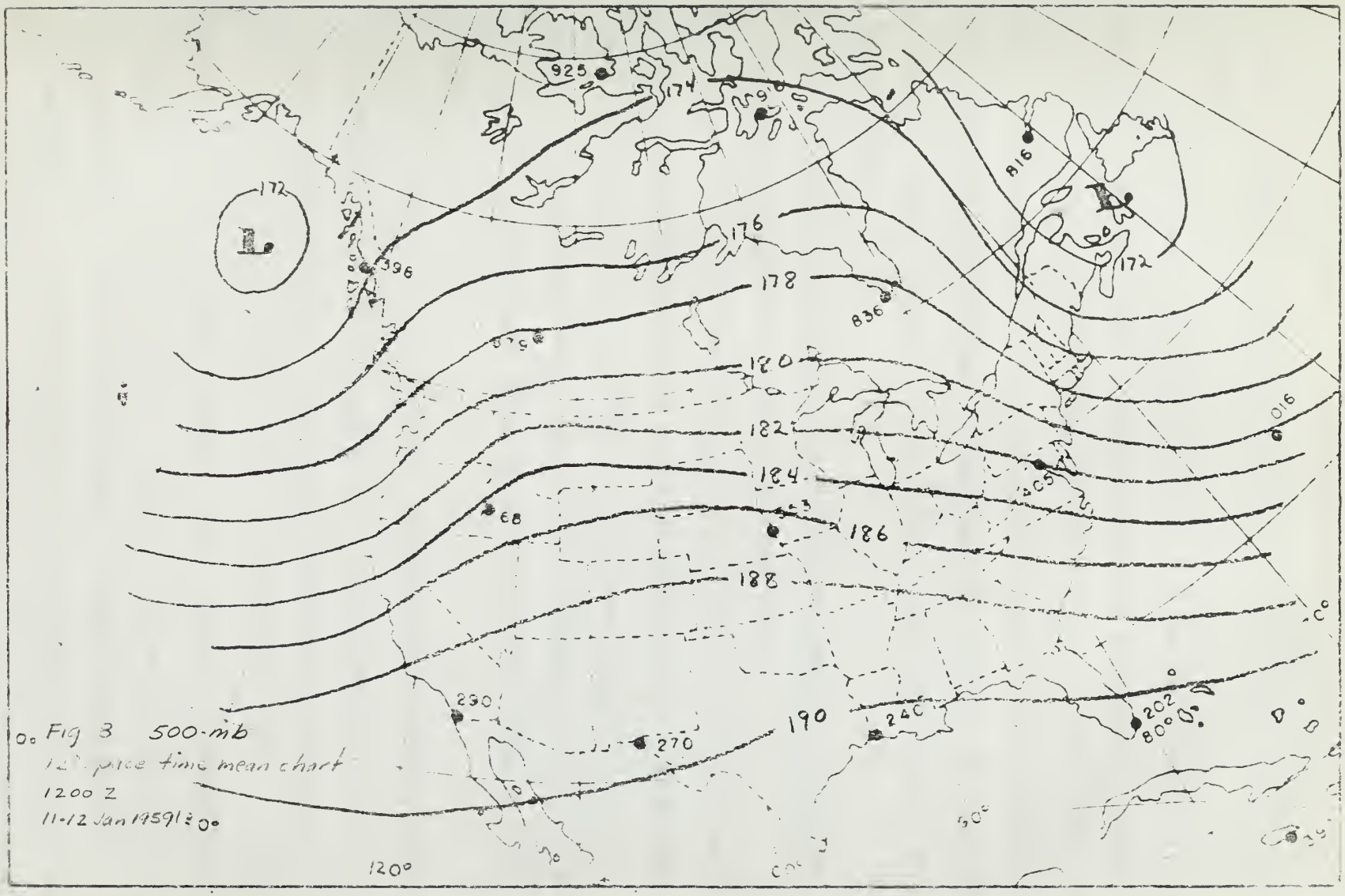


Fig 3 500-mb
12-hour space time mean chart
1200 Z
11-12 Jan 1959

because our prognostic techniques were compared with persistency, an evaluation of persistency as a 100-mb tool was made. Results, in general, excelled all other forecast techniques.

Persistency appeared to have a somewhat irregular cyclical variation but forecasting when periods of change will occur is a task approaching the scope of the basic problem of this paper. A few subjective attempts were made to forecast the occurrence of changes but because of the limited amount of data and lack of success, the investigation was terminated.

2. Vertical Extrapolation of 100-mb heights using 500-mb space-mean heights and relative vorticity.

An extrapolation technique for determining 100-mb heights was developed and is similar to that of Vederman and Dubofsky [10] at 200 mb. A graph of 100-mb height versus 500-mb space-mean height and relative vorticity was constructed using data from 19-21 and 26-28 January 1959. (fig. 9)

The use of this graph as a prognostic technique requires the construction of a prognostic 500-mb space-mean and relative vorticity chart. The space mean of the prognostic 500-mb chart is obtained using the 12° square grid (see paragraph C 1 of this chapter). The relative vorticity is obtained by subtracting the 500-mb prognostic heights from the prognostic space-mean heights. Using the subject parameters, the 100-mb heights are determined from figure 9 for enough points to allow analysis of the isohyptic field.

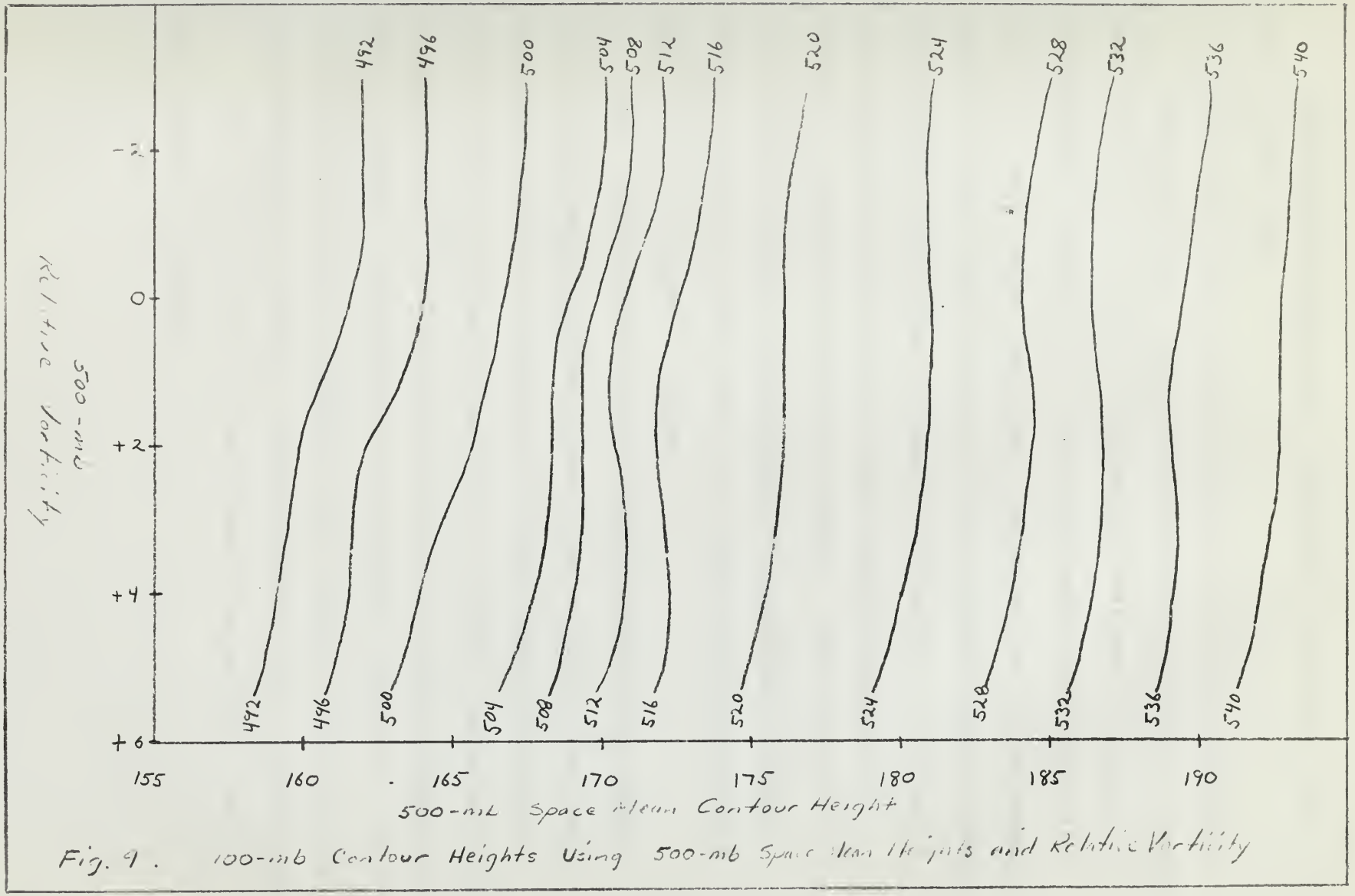


Fig. 9. 100-mb Contour Heights Using 500-mb Space Mean Heights and Relative Vorticity

No prognoses were made using this technique thus it was not evaluated.

3. 24-hour height change patterns in 100-mb prognosis.

24-hour height change centers were computed at 500 mb and 100 mb in an effort to correlate movement and magnitude at these two levels [11] . The short-wave influences at 500 mb in most cases completely dominated the height-change pattern so that association of 100-mb height-change centers with 500-mb centers was extremely difficult. An attempt was made to use 500-mb space-mean height changes in an effort to eliminate short-wave effects. This method was unsuccessful because the magnitude of space-mean height-change centers was too small to be effectively associated with 24-hour changes at 100 mb.

The 100-mb 24-hour height-change centers are generally of less magnitude than those found at 500 mb and progress generally in the direction of the 100-mb space-mean flow. Speed of movement, however, is erratic, being at times as great as 15° latitude in 24 hours and at other times slowing to a speed more analogous to long-wave movement. Extrapolation of movement of height-change centers was attempted as a prognostic technique, but the results were inconclusive.

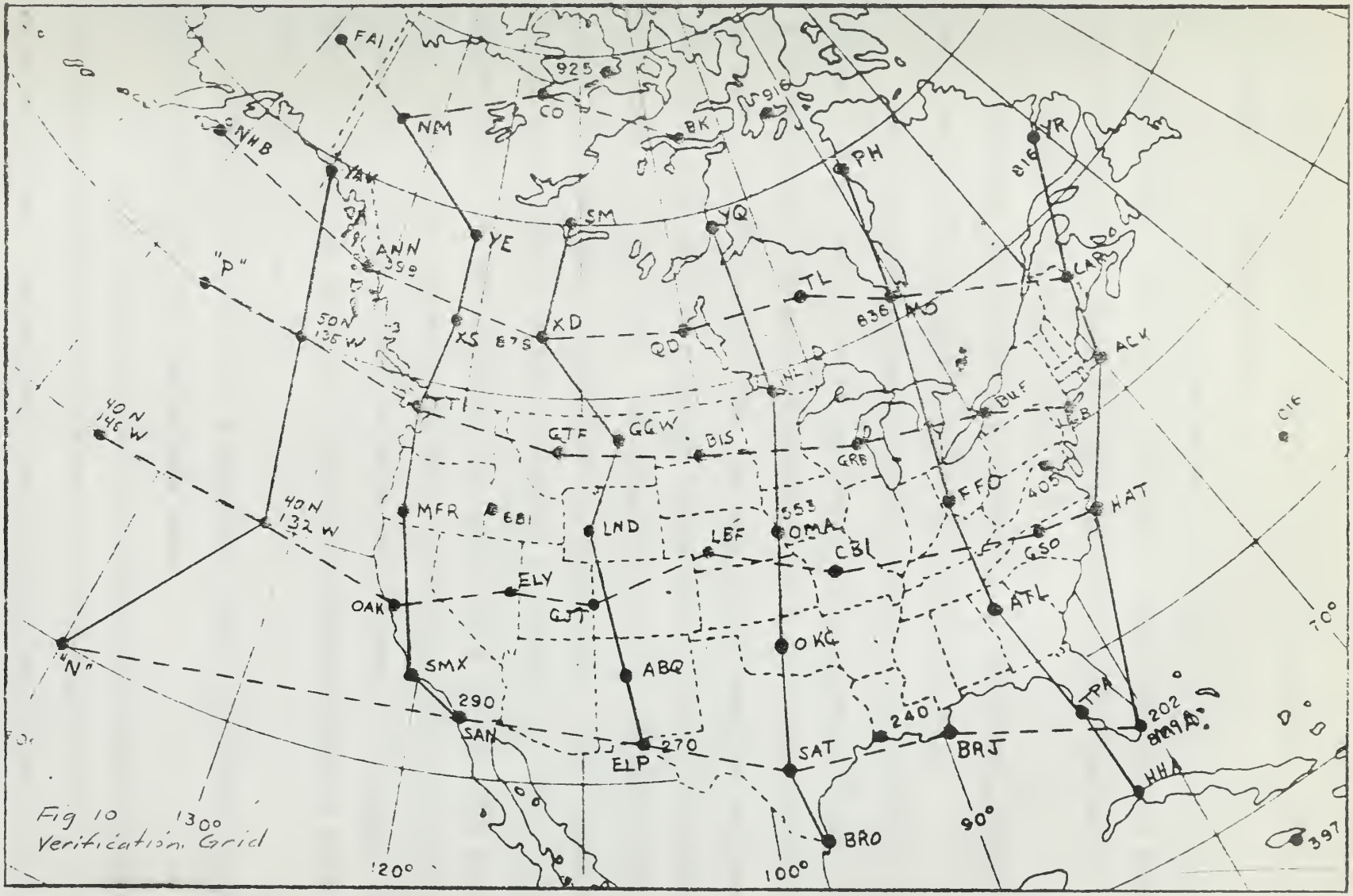
This investigation is considered incomplete; evaluation was not attempted.

IV. Evaluation of Selected Prognostic Techniques

Evaluation of three of the several prognostic approaches described in Chapter III is discussed here. The primary evaluator was grid score, but shape relationship and single station forecasts of geostrophic wind and contour height were also used.

The verification grid used (fig. 10) is that presently in use at the United States Naval Postgraduate School for student forecast evaluation. The grid consists of 54 stations located in the United States and Canada and includes five oceanic stations off the west coast. East-west and south-north contour height gradients are computed for the prognostic and the verification-time analyzed chart. Gradient errors are computed, for each grid interval, as the absolute value of the algebraic difference between the analyzed and prognostic gradient. The grid score is the ratio of the sum of the individual gradient errors to the sum of the absolute value of the analyzed gradients. The lower the grid score the better the prognosis. This particular grid, where distance between grid points averages approximately 250 nautical miles, best evaluates the movement and gradient associated with long-wave systems and thus is especially applicable to 100-mb verification.

Shape relationship was not a primary evaluation tool although it was considered necessary for a good prognosis. In general, shape resemblance and low grid scores were coincident, but many "look-alike" charts yielded relatively mediocre scores. Primary features noted were the relative


FAI
925
CO
916
NM
BK
NHB
YAK
PH
YR
SM
YQ
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ANN
359
"P"
50N
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XD
QD
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836
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CAR
ACK
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YUL
CYQ
40 N
146 W
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GGW
BIS
GRB
FFO
405
HAT
MFR
681
LND
LBF
OMA
553
CBI
GSO
40N
132 W
ELY
OAK
GJT
ATL
OKC
"N"
SMX
ABQ
290
SAN
270
ELP
SAT
240
BRJ
TPA
202
MIA
HHA
BRO
90°
100°
120°
130°
70°
397
Fig 10
Verification Grid

positions of troughs, ridges, closed circulations, and areas of weak or tight gradient.

Spot forecasts were made for eleven stations in three latitude belts (fig. 11). Forecasts were verified in each latitude group as well as collectively. Spot forecast results are contained in table III.

A. Graphical addition of a monthly mean 500/100-mb thickness pattern and the 500-mb 24-hour contour prognosis.

This technique was used over the period 2 through 20 January 1959 (with the exception of 15 January 1959 for which a 500-mb chart was not available). The grid scores are shown in table I, column IV. The average grid score for eighteen days was 0.50 with a standard deviation of 0.11. The range was from 0.27 to 0.72. The prognosis for 14 January 1959, using this technique, is shown in figure 12. The actual 100-mb chart for 14 January 1959 is shown in figure 19. The pattern resemblance is fairly good; the grid score 0.45. The prognosis and the actual 100-mb chart for 12 January 1959 are shown in figures 13 and 17. This particular prognosis was among the worst using this method. The pattern resemblance is poor and the grid score is 0.70.

B. Graphical addition of a modified mean 500/100-mb thickness pattern and a 500-mb space-time mean.

The technique of graphically adding the modified mean thickness pattern to the 500-mb space-time mean was also evaluated by pattern resemblance and the grid verification method. This technique was applied to the data from 2 through 14 January 1959. The grid scores are shown in table I, column V.

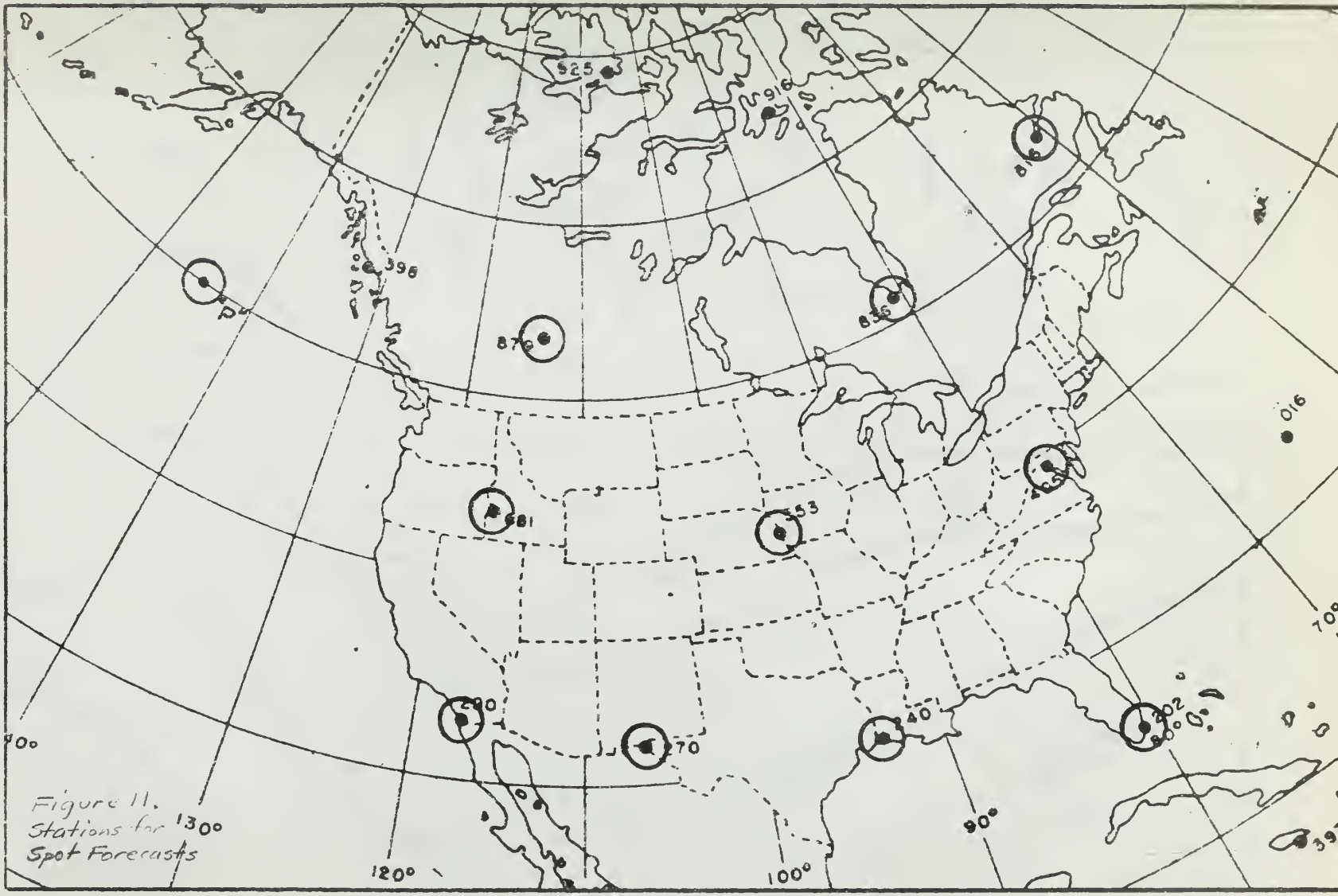


Figure 11.
Stations for
Spot Forecasts

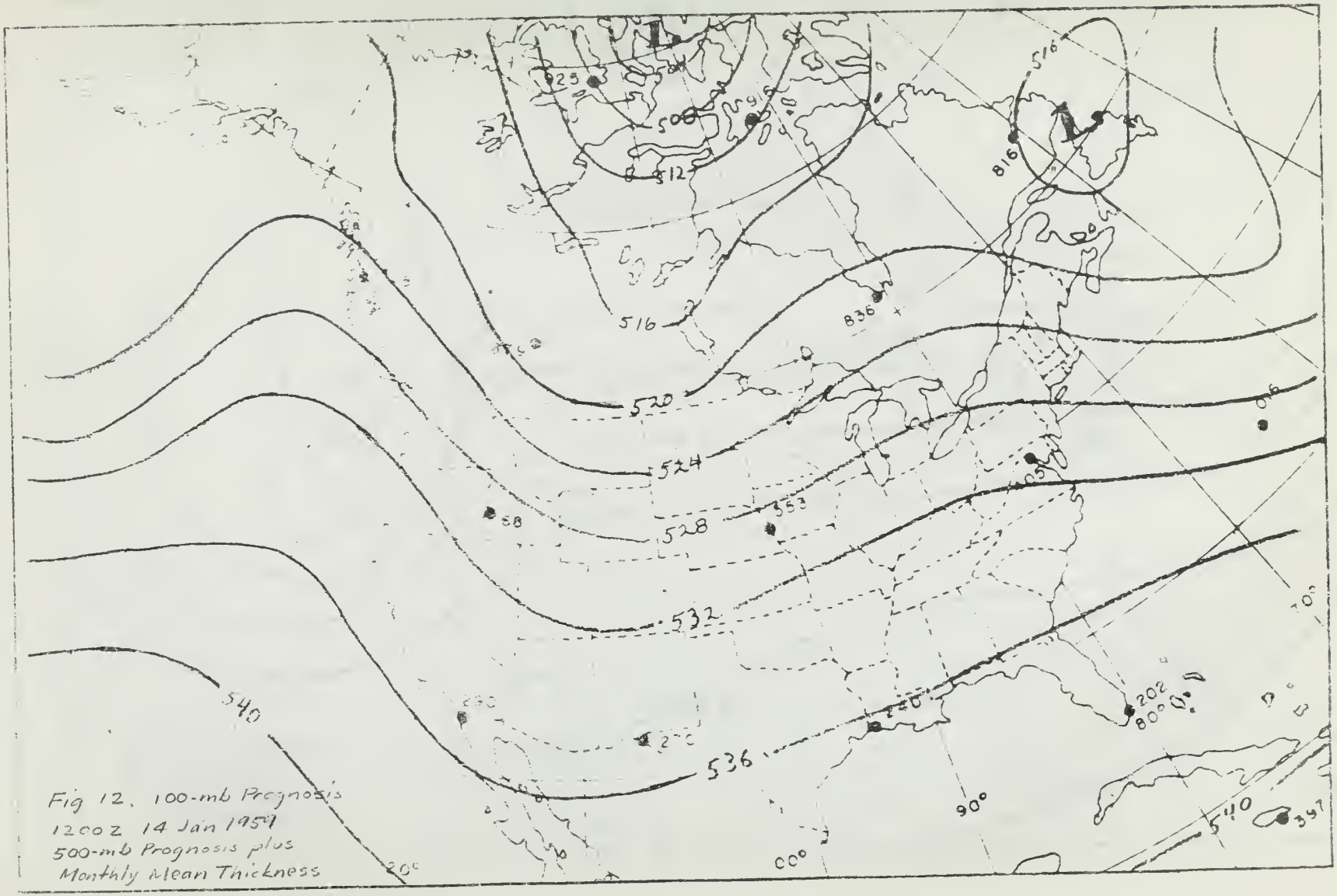


Fig 12. 100-mb Prognosis
1200Z 14 Jan 1954
500-mb Prognosis plus
Monthly Mean Thickness

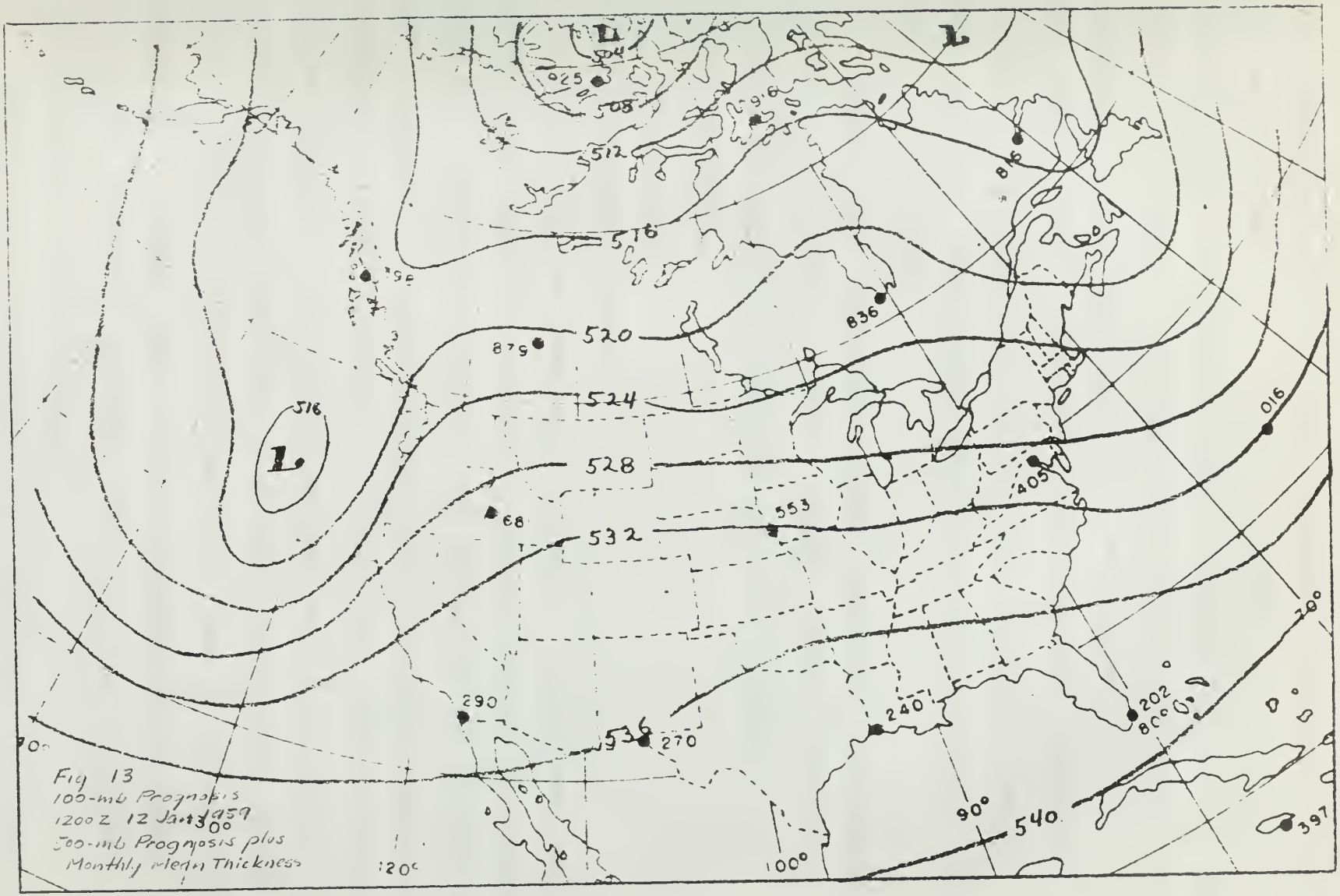


Fig 13
100-mb Prognosis
1200 Z 12 Jan 1959
500-mb Prognosis plus
Monthly Mean Thickness

The mean grid score is 0.42 with a standard deviation of 0.06. The range is from 0.32 to 0.55. An example of a prognosis made using this technique is shown in figure 14. This prognosis gave a good estimate of trough positions and the general flow pattern. The grid score is 0.40. The prognosis for 14 January 1959 is shown in figure 15. This prognosis, although locating the troughs very well does not adequately indicate the amplitude. The forecast flow is excessively zonal. The grid score is 0.51.

Both of the above methods were evaluated for prognoses derived in a strictly objective manner, although there were areas where subjective smoothing would have resulted in a better prognosis.

C. Persistence

1. Prognostic charts

Persistency was evaluated by pattern resemblance, grid verification and spot forecasts of contour height and geostrophic wind direction and speed. The evaluation was carried out for the months of January 1959 and 1960. The grid scores are contained in table I, column II. The average grid score for the two months is 0.38 with a standard deviation of 0.09. The range is from 0.21 to 0.58. As examples, the actual 100-mb patterns for 11 through 14 January are shown in figures 16-19. Using the 11 January analysis as a prognosis for 12 January a grid score of 0.30 is obtained. Also note the very good resemblance between the two patterns.

Persistency has relatively poor days too, an example of which is shown in using 13 January 1959 as a prognosis for 14

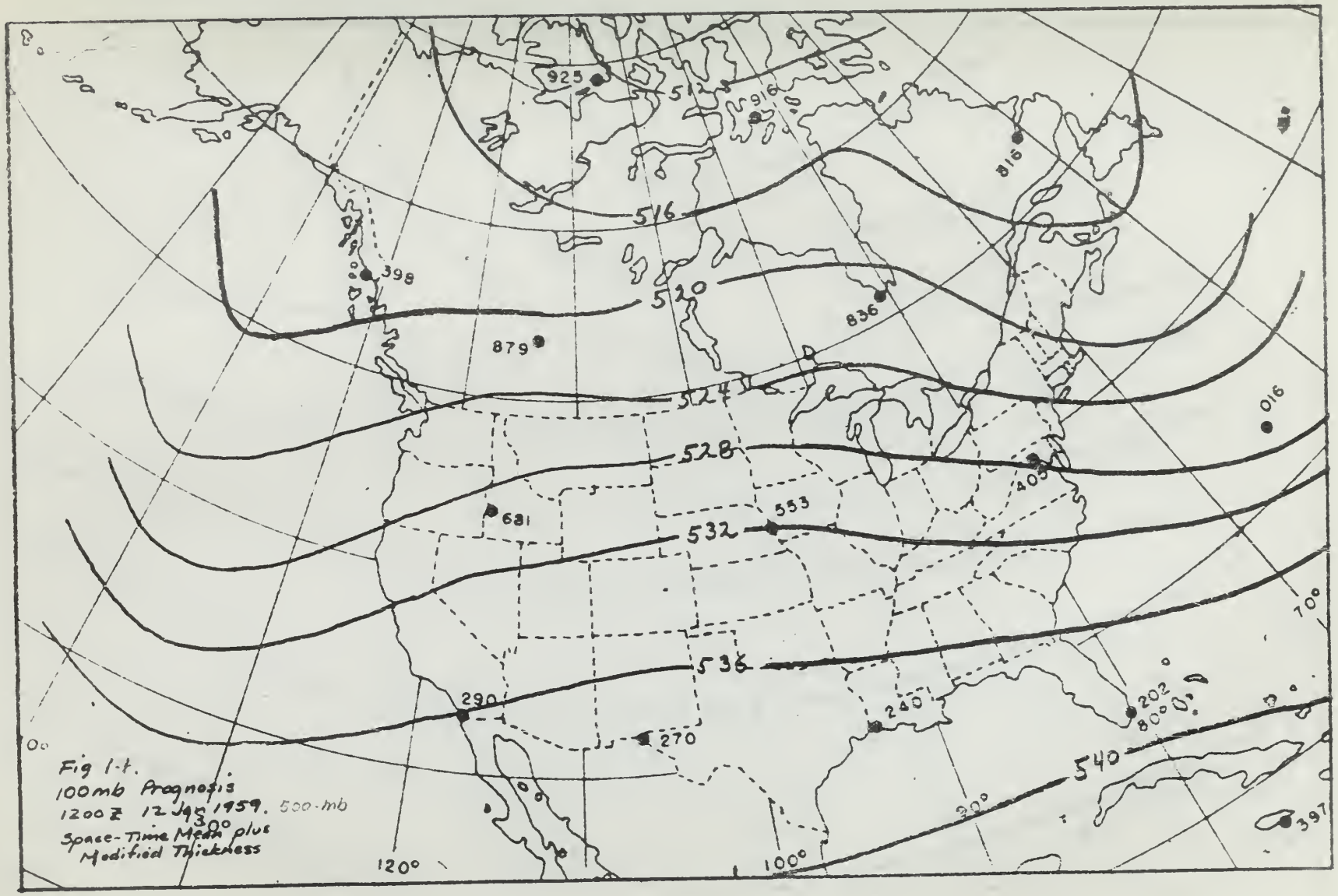


Fig 1-t.
100mb Prognosis
1200Z 12 Jul 1959. 500-mb
Space-Time Mean plus
Modified Thickness

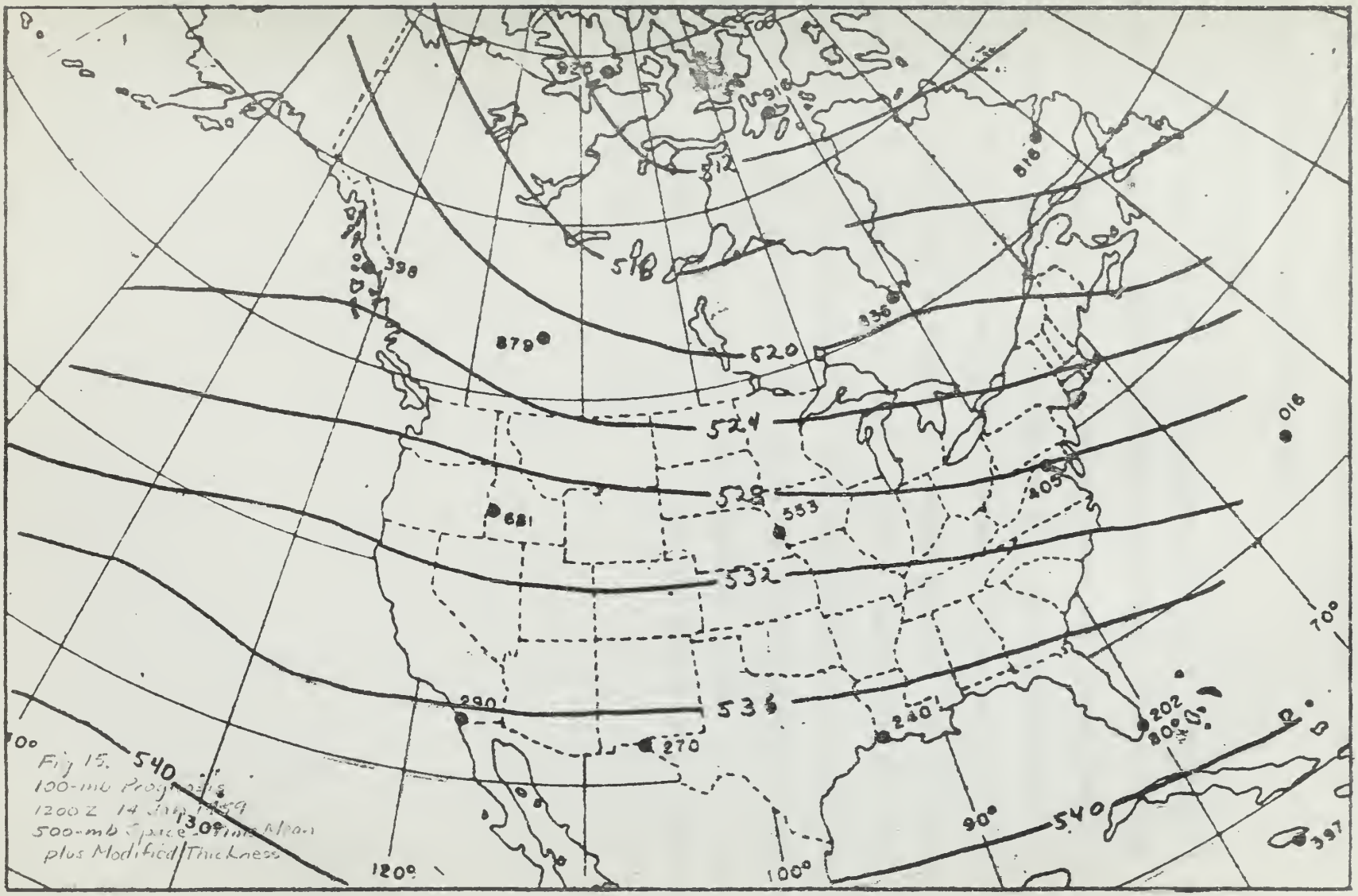


Fig 15.
100-mb Prog
1200 Z 14 Jan
500-mb Space
plus Modified Thickness

January 1959. The grid score, 0.57, is accompanied by poor pattern resemblance with the exception of the area between 50° and 90° west longitude. This date represents one of the poorest prognoses using persistence.

2. Spot Forecasts

The largest errors in the spot forecasts (table III) of wind direction and contour height were found at the higher latitudes, however, the wind speed error was found greatest in the lower latitudes. It is normal for the larger errors in wind direction in a persistence forecast to be at the higher latitudes since the majority of closed systems at 100 mb move through this region. The large speed error found in the lower latitudes can be explained by the proximity of the sub-tropical jet to the four stations for which the spot forecasts were made. Fluctuations in the position and strength of the jet in the vicinity of these stations gives rise to relatively large speed fluctuations from day to day.

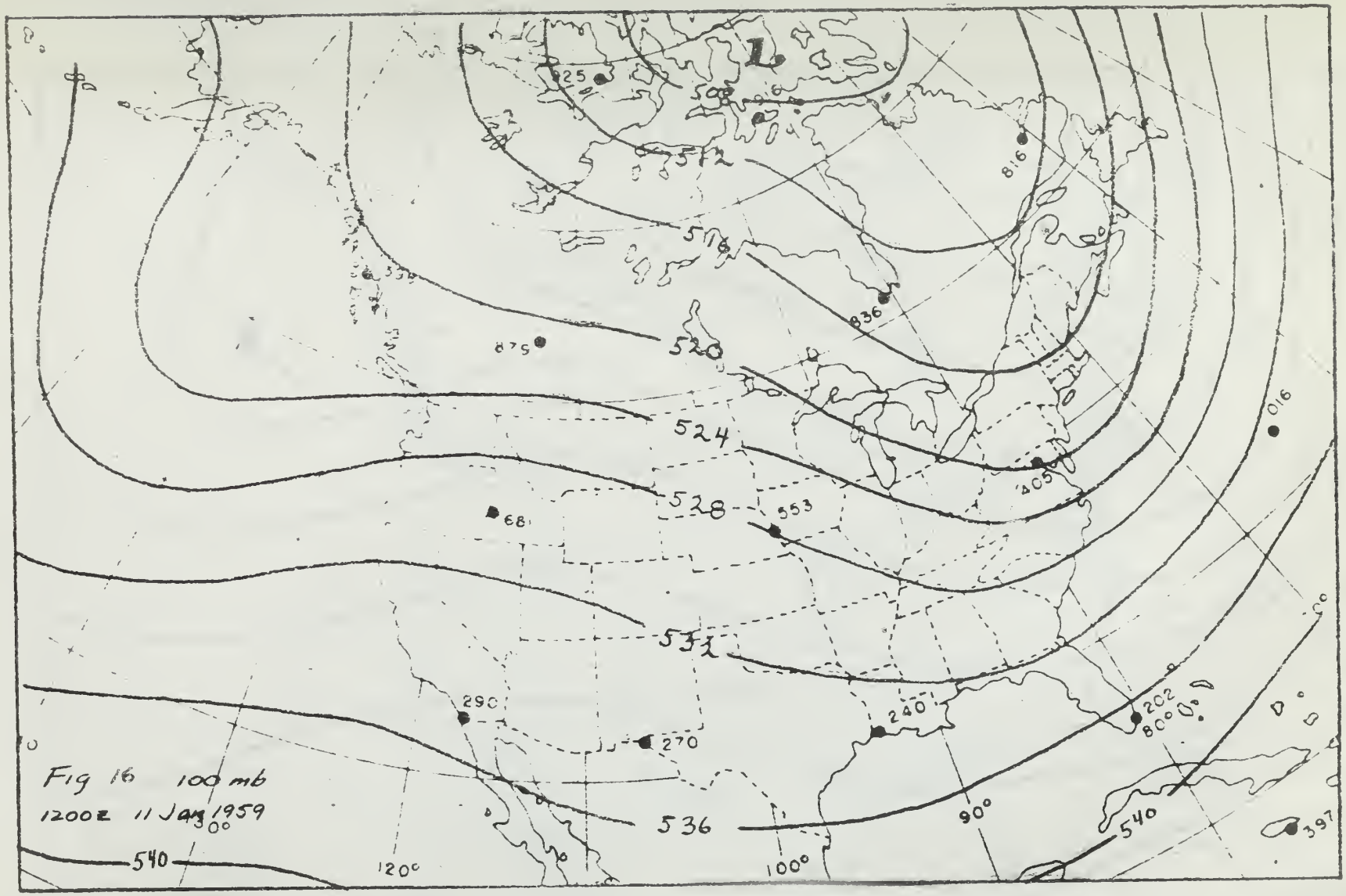
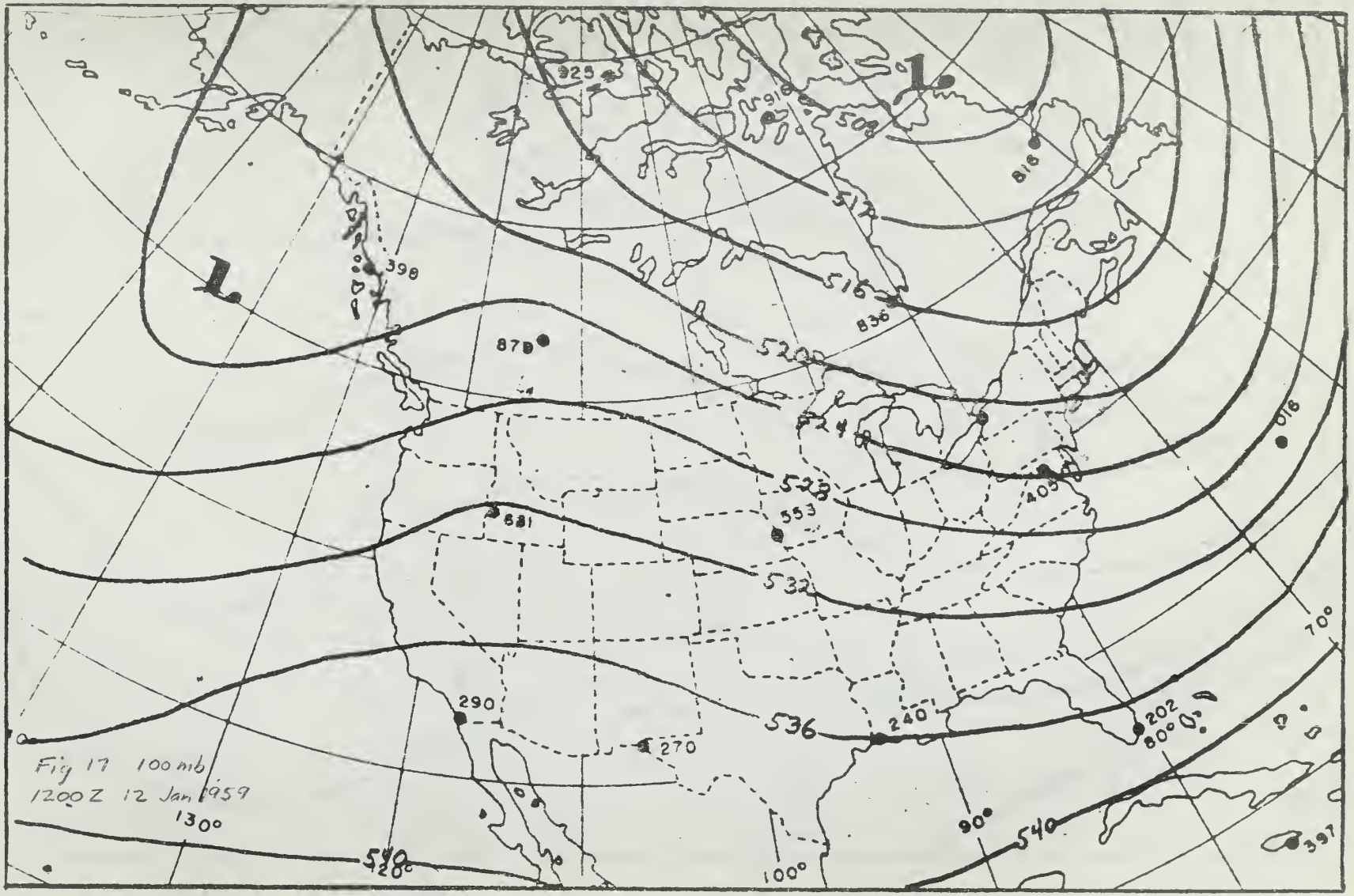


Fig 16 100 mb
1200Z 11 Jan 1959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80°
90°
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Fig 17 100 mb
1200Z 12 Jan 1959

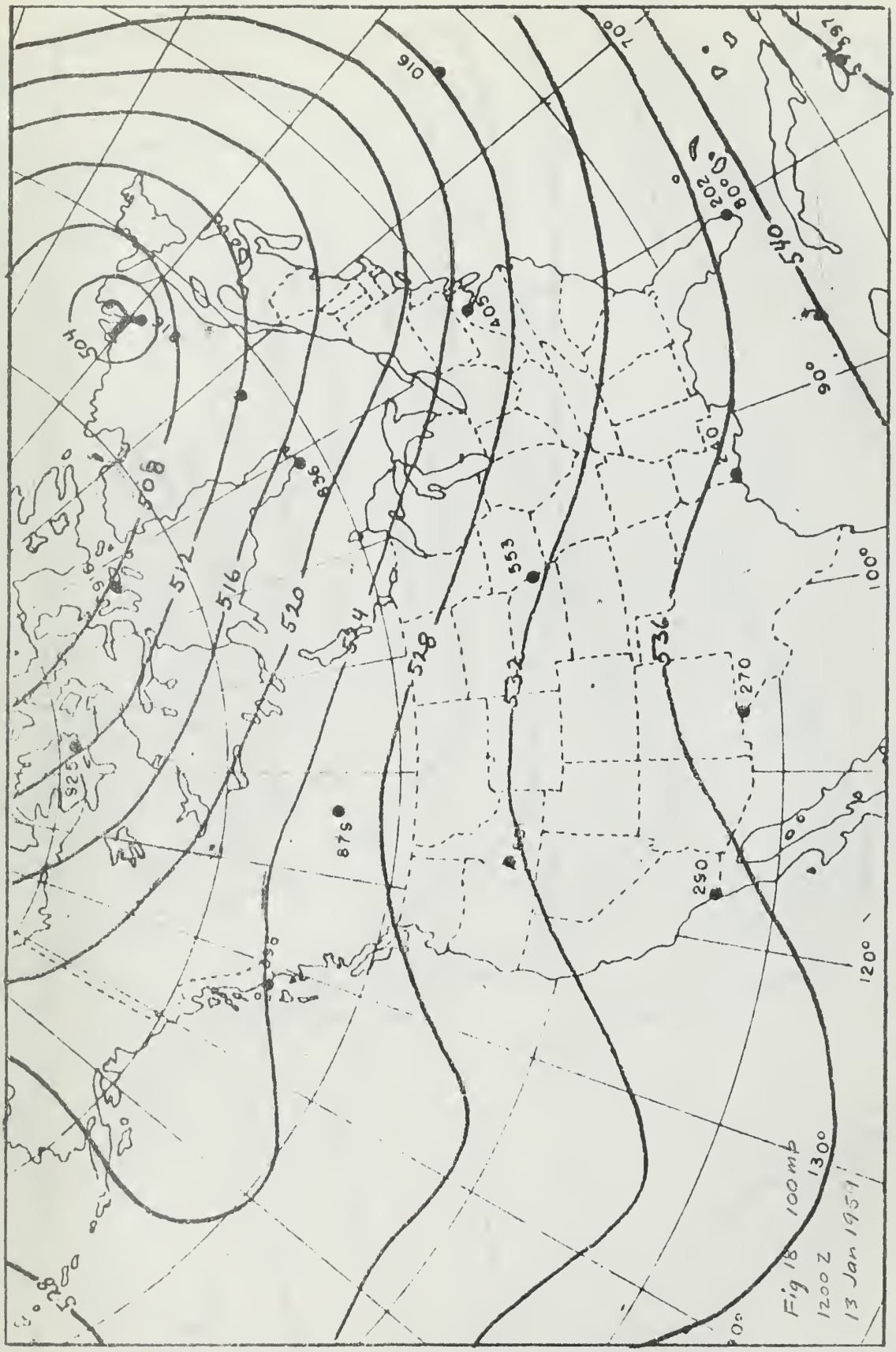
Fig 18 100 mb
1200 Z
13 Jan 1951

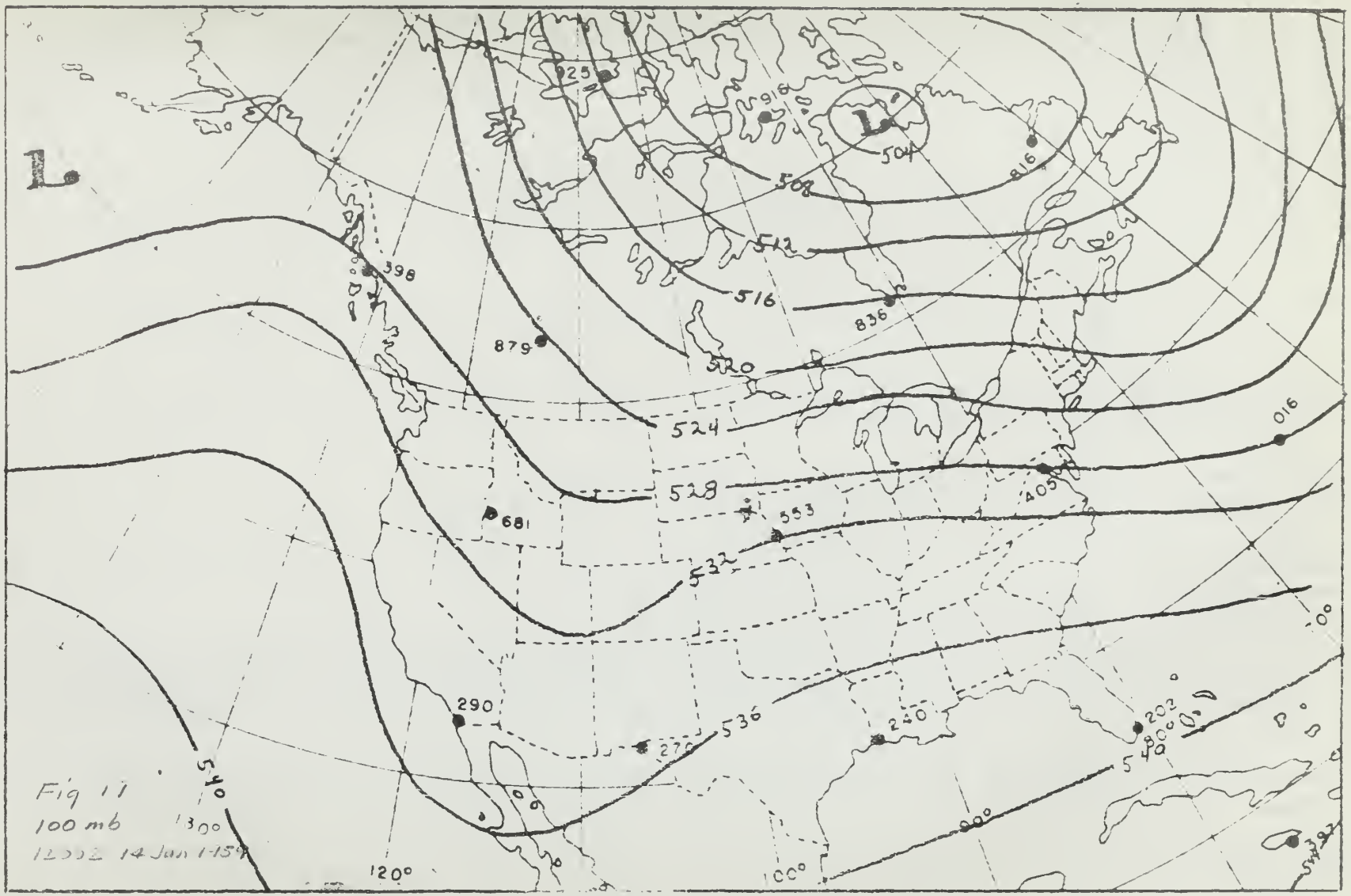

Fig 11
100 mb 1300
12552 14 Jan 1959

TABLE I

DAILY GRID-VERIFICATION SCORES

DATE - JAN	100's ft TOTAL GRADIENT 1959 I	PERSISTENCE 1959 II	MEAN 100-MB PATTERN 1959 III	500-MB PROG PLUS MEAN THICKNESS 1959 IV	500-MB SPACE-TIME MEAN PLUS MOD THICKNESS 1959 V	100's ft TOTAL GRADIENT 1960 I	PERSISTENCE 1960 II	MEAN 100-MB PATTERN 1960 III
1			0.45					0.80
2	257	0.44	0.50	0.42		167	0.35	0.61
3	289	0.37	0.48	0.27	0.38	131	0.38	0.46
4	132	0.31	0.49	0.33	0.32	190	0.26	0.41
5	261	0.41	0.46	0.51	0.40	233	0.31	0.50
6	232	0.51	0.51	0.49	0.42	200	0.52	0.45
7	221	0.50	0.56	0.47	0.40	208	0.38	0.51
8	198	0.31	0.53	0.51	0.34	208	0.44	0.47
9	115	0.39	0.52	0.72	0.42	195	0.46	0.46
10	171	0.41	0.48	0.51	0.41	204	0.36	0.44
11	179	0.33	0.44	0.53	0.40	201	0.36	0.39
12	195	0.36	0.45	0.70	0.42	211	0.41	0.56
13	161	0.38	0.49	0.54	0.55	186	0.32	0.50
14	181	0.51	0.41	0.45	0.51	191	0.37	0.53
15	241	0.41	0.41			197	0.43	0.54
16	250	0.41		0.52		190	0.50	0.63
17	230	0.42		0.42		185	0.61	0.60
18	191	0.41	0.41	0.44		187	0.58	0.81
19	220	0.41	0.47	0.45		178	0.48	0.65
20	230	0.41	0.42	0.50		177	0.21	0.79
21	222	0.43	0.43			161	0.41	0.34
22	222	0.37	0.49			145	0.50	0.41
23	252	0.47	0.47			174	0.28	0.75
24	230	0.45	0.44			181	0.37	0.62
25	240	0.42	0.41			232	0.34	0.43
26	248	0.38	0.46			234	0.32	0.47
27	215	0.44	0.48			235	0.28	0.40
28	232	0.38	0.51			233	0.41	0.45
29	211	0.38				225	0.34	0.56
30	218	0.41	0.51			171	0.46	0.61
31	191	0.41	0.47			204	0.37	0.75

TABLE II

GRID VERIFICATION STATISTICS

	PERSISTENCE	MEAN 100-MB PATTERN	500-MB PROG +24HRS MEAN THICKNESS	500-MB SPACE-TIME MEAN PLUS MOD MEAN THICKNESS
AVERAGE SCORE	0.38	0.55	0.50	0.42
STANDARD DEVIATION	0.09	0.13	0.11	0.06
RANGE	0.21 - 0.58	0.36 - 0.84	0.27 - 0.72	0.32 - 0.55

TABLE III ERRORS IN 100-MB SPOT FORECASTS USING PERSISTENCE AS A PROGNOSIS

	HIGH LATITUDES ~50°	MIDDLE LATITUDES ~40°	LOW LATITUDES ~30°	ALL STATIONS
CONTOUR HEIGHT				
Average Error (feet)	217	182	142	180
Standard Error (feet)	290	250	180	240
[illegible] MLED				
Average Error (m.p.h.)	13.3	11.5	[illegible]	11.3
Standard Error (m.p.h.)	[illegible]	15.4	[illegible]	16.3
GEOS WIND [illegible]				
Average [illegible] (m.p.h.)	24.2	16.1	13.3	17.5
[illegible]	34.6	19.8	15.7	26.0

TABLE IV COMPARISON OF [illegible] ANALYZED HEIGHTS WITH [illegible] HEIGHTS

	HIGH [illegible] ~50°	MIDDLE [illegible] ~40°	LOW LATITUDE ~30°	ALL STATIONS
AVG. [illegible] (FT)	88	69	76	77
STD. [illegible] (FT)	138	93	77	116

V. Conclusions and Comments

1. The basic results of this study corroborate the work of Ellsaesser [2,3] in that persistence is the optimum method for 24-hour 100-mb prognosis. Present requirements for 100-mb prognosis are for flights of duration considerably less than 24 hours and these requirements are certainly met by a persistence prognosis. Further, the 24-hour prognostic chart is available immediately upon completion of the current analysis.

The accuracy of the persistence 100-mb prognosis, as determined using grid verification scores, averaged considerable lower (better) than lower level scores. Good conventional prognoses using the same grid verification at 500 mb generally yield grid scores between 0.40 and 0.60, thus a 100-mb technique using the 500-mb prognosis would have to reduce the effect of the gradient errors at 500 mb in order to produce a good 100-mb prognosis.

2. Other prognostic techniques, similar to those encompassed in this study, show promise, however natural extrapolation techniques in general suffer from the inability to adequately forecast the change of the thermal structure of a thick layer. When the layer includes the tropopause, the problem is greatly magnified. Thus, extrapolation through the 35,000 foot layer between 100 and 500 mb is a poor prognostic procedure, however, until more accurate prognoses of layers above 500 mb are available this appears to be the only practical level from which to work.

A mean thickness pattern appears to be more useful than individual extrapolations, since the entire chart is produced in the process and no further analysis is necessary. The mean patterns used in this investigation produced very creditable prognoses in view of the limited research that led to their development. Mean thickness patterns based upon a shorter time span may more adequately portray the prognostic 500/100-mb thickness pattern.

During periods of maximum change in the 100-mb contour pattern, the techniques of graphical addition of the mean thickness pattern to the 500-mb prognosis and the modified thickness pattern to the space-time mean resulted in prognoses that had better pattern resemblance and lower grid scores than persistence. This would lead to a combination of persistence and mean-thickness techniques as an optimum method of prognosis.

3. The space mean chart of Panofsky, et al, [9] has no advantage over persistence for 100-mb forecasts. The 500-mb space-mean pattern, reflecting the closed circulations at 500 mb to a large degree, requires considerable modification to be used as a 100-mb prognostic chart.

4. The investigation of the graphical addition of the current daily thickness pattern and the 500-mb space mean chart showed considerable promise before it was terminated. This procedure is based on the space smoothing of 500-mb contours, which minimizes short waves, plus the persistence of the space smoothed pattern and the thickness pattern. The early success of this method as a prognostic technique

suggests further study.

5. The performance of the mean January 100-mb chart [12] (table I column III) in the grid verification substantiates Ellsaesser's[2,3] conclusion that climatology is the best forecast technique for periods greater than 24 hours. Although several individual prognoses were poor the overall average is considerably better than might be expected using any other technique.

6. The prognosis of individual features (troughs, ridges, lows, etc.) at 100 mb is impractical. Pattern forecasts appear most reliable.

7. Analysis at 100 mb using a 400-foot contour interval does not adequately reflect contour gradient, especially in the vicinity of the jet streams. The limited number of reporting stations might make analysis using a smaller interval more difficult, however, geostrophic gradients would be more accurately represented and the wind field in areas of few reports would be better portrayed.

8. An evaluation was also made of the relationship between heights as reported and heights as analyzed using the 100-mb analyses for January 1959 and 1960. The standard error between these two heights was found to be 116 feet which compares very well with the instrument error of Muench [6] . (see table IV)

9. Vertical time cross-sections constructed at several stations preliminary to the investigation of prognostic procedures indicated that perhaps more short wave features occur at 100 mb than are presently analyzed. This study,

far from conclusive, suggests the inaccuracy of analysis techniques which minimize the presence of 100-mb short waves.

Comparing the reported and analyzed heights indicate that, in general, analyses average within the 128 foot standard error of reported values [6]. An attempt to associate the difference between reported and analyzed heights with short wave phenomena determined from time cross sections may verify the authors' contention that short waves are, in effect, "analyzed-out" of 100-mb charts.

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